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13. ABSTRACT *(Maximum 200 words)*

Nonlinear interactions in fibers, primarily for applications to all-optical switching devices, have been investigated.

1. The theory of all-optical switching with gain in erbium-doped dual core fibers has been developed.
2. Several and various experiments were performed in nonlinear fiber rocking filters.
3. A femtosecond infrared (1650 nm) source has been built.
4. An APM color center laser (300 fsec - 1 psec pulse width) has been constructed.
5. A new mechanism for soliton compression has been demonstrated.
6. A dual frequency, cw color center laser has been constructed.
7. The periodic evolution into dark solitons of a pulsed two color source has been demonstrated.
8. Photoinduced gratings in Ge doped sol-get films have been demonstrated.
9. Nonlinear fiber-optic experiments in tapered fibers have been attempted.

14. SUBJECT TERMS
Nonlinear fiber optics; all-optical switching; nonlinear properties of fibers and glasses; switching with gain; erbium doped dual core fibers; soliton switching; soliton interactions

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Title: Nonlinear Fiber Optics

Author of Report: G.I. Stegeman, CREOL, University of Central Florida

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Subject Terms: Nonlinear fiber optics; all-optical switching; nonlinear properties of fibers and glasses; switching with gain; erbium doped dual core fibers; soliton switching; soliton interactions

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Summary:

Nonlinear interactions in fibers, primarily for applications to all-optical switching devices, have been investigated.

1. The theory of all-optical switching with gain in erbium-doped dual core fibers has been developed. It predicts very sharp switching thresholds and gain to make fan-out possible. A source of dual core doped fibers has been found and initial fibers evaluated.

2. A number of experiments have been performed in nonlinear fiber rocking filters. These include:
   (a) All-optical switching in rocking filter fibers for single beam inputs has been demonstrated on and near the filter resonance.
   (b) Phase-controlled switching of a strong beam with a weak beam has been demonstrated for the first time in all-optical switching.
   (c) All-optical logic gates have been demonstrated using the asymmetric response of a nonlinear fiber rocking filter detuned from resonance.
   (d) Demultiplexing has been demonstrated in a pump-probe geometry.
   (e) In collaboration with Ken Hill, we have designed and tested a nonlinear fiber rocking filter for soliton switching at 1555 nm.

3. A femtosecond infrared (1650 nm) source has been built based on difference frequency mixing a dye laser output with 1064 nm radiation from a mode-locked Nd:YAG laser.

4. An APM color center laser (300 fsec → 1 psec pulse width) has been constructed.

5. A new mechanism for soliton compression based on high mode dispersion has been demonstrated.

6. A dual frequency, cw color center laser has been constructed.

7. The periodic (with distance, time and power) evolution into dark solitons of a pulsed two color source has been demonstrated.

8. Photoinduced gratings in Ge doped sol-gel films have been demonstrated.

9. Nonlinear fiber-optic experiments in tapered fibers have been attempted.

Research Objectives:

1. To study all-optical switching in fibers, with and without gain.

2. To study soliton interactions and soliton switching in fibers, and to build the laser systems needed for these investigations.

3. To finish work on photosensitivity in glasses started under the preceding grant.

Final Report:

This program started in November 1990, about two months after this laboratory moved from the Optical Sciences Center of the University of Arizona to CREOL of the University of Central Florida. It was for a total time period of two years. A number of fiber projects were moved with their personnel, including three graduate students and one postdoctoral fellow. A number of these projects are now completed. Some will continue to completion after this contract terminates.

1. All-Optical Switching in Active Nonlinear Directional Couplers

The goal here was to investigate all-optical switching in a dual core fiber (see Fig. 1) in which both gain and complete switching (no pulse break-up) are achieved. The all-optical response of a dual core fiber with erbium-doped core concentrations of a few hundred ppm was modelled using a combination of coupled mode theory and beam propagation techniques. Gain was assumed by exciting the erbium atoms with pump beams at 514, 980 or 1480 nm, with dopings chosen so that the excitation drops to approximately

1/2 over the length of the device. In order to achieve complete switching without pulse break-up, a temporal soliton input was assumed with coupler lengths of a few soliton periods (4 in this case).

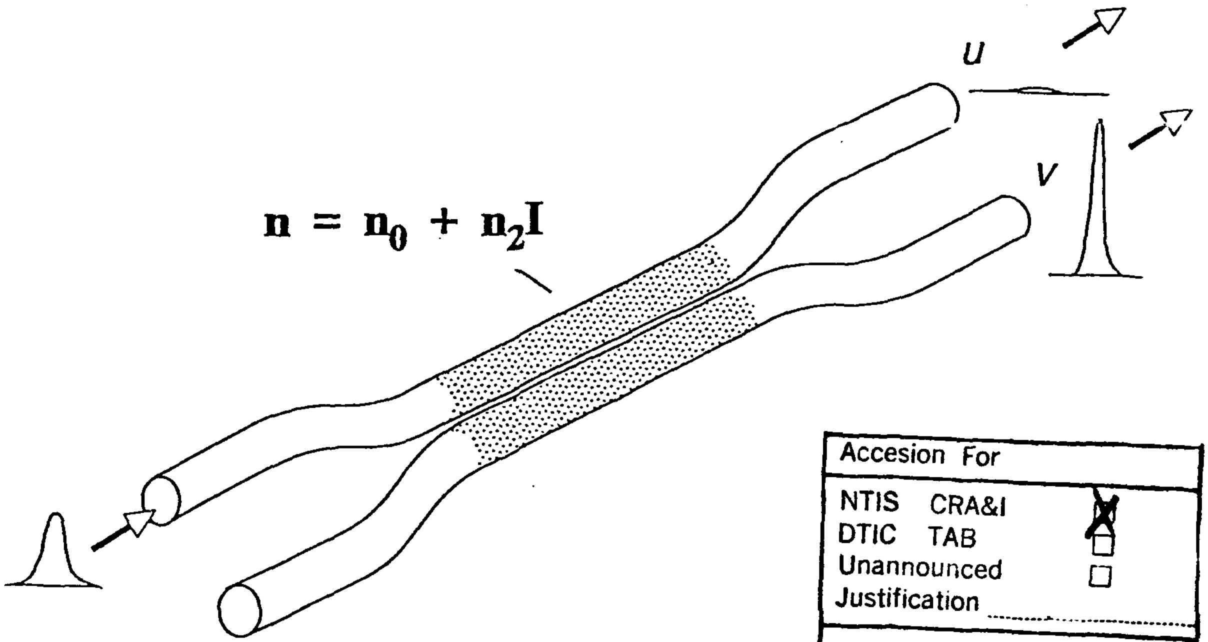

Fig. 1 *The nonlinear directional coupler fiber geometry with erbium doped cores.*

The calculations predict complete switching, much sharper switching thresholds than for the case without gain, and pulse compression.[1,2] The predicted switching characteristic is shown in Fig. 2. The combination of gain and pulse compression led to a net increase in the peak output intensity by a factor of 36 for the conditions studied. The results look very attractive for switching with fan-out for pulses whose bandwidth fits within the bandwidth of the erbium gain at 1520 nm, i.e. pulses longer than 1 picosecond.

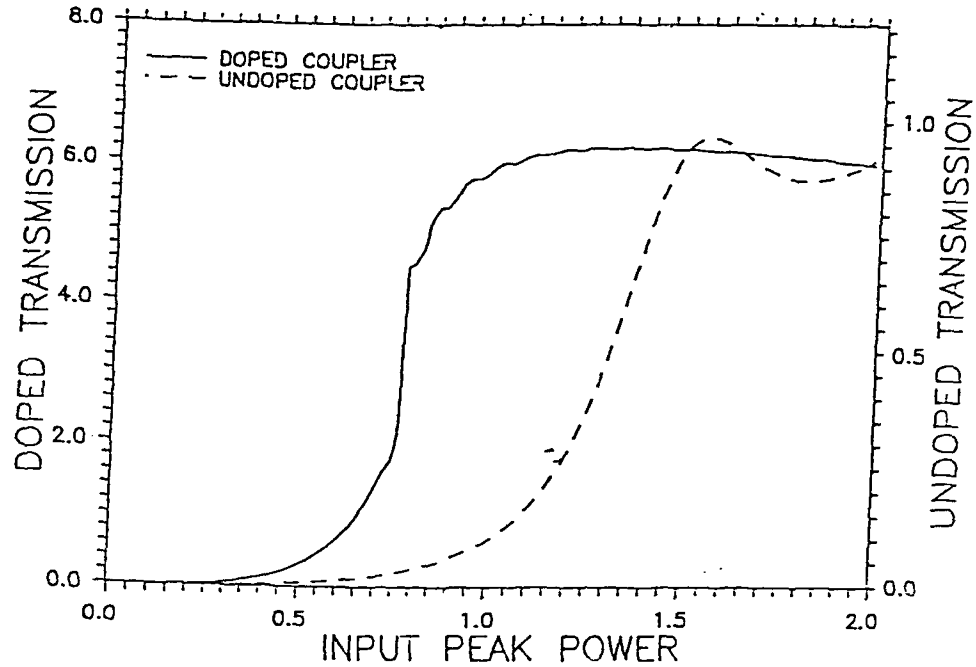

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Fig. 2 ***The switching characteristics of dual core nonlinear directional coupler with gain (left) and a passive coupler (right).***

Some limited progress has been made in the experimental implementation of these ideas. A collaboration with Professor Pak Chu's group at the University of New South Wales in Sydney Australia has recently been established. This Australian group has successfully made dual core fibers with one or both cores doped with erbium atoms for operation at 515 nm. We tested their fibers for operation at 1520 nm. Because these fibers were originally made for operation at 515 nm, a number of them were cut-off at 1525 nm. For the ones which still guided at 1525 nm we found essentially no power transfer between the two cores. The Australian group has promised to try again, and hopefully this work will continue to a successful conclusion.

2. All-Optical Switching Experiments in Fiber Rocking Filters

A number of all-optical phenomena have been demonstrated in rocking fiber rocking filters obtained from Roger Stolen of ATT Bell Labs. In terms of versatility these devices rival nonlinear loop mirrors and offer more options that soliton dragging gates.

The basic concepts are as follows. The fibers are weakly birefringent so that $n_x \neq n_y$. The plane of polarization of light of wavelength λ_c is rotated with propagation distance (z) in a fiber rocking filter, provided that the fiber birefringence beat length (at λ_c) equals the period of the twist deliberately imparted to the

fiber during fabrication. Detuning λ from λ_c reduces the net rotation angle for a given fiber length. Detuning is also achieved by using high optical intensities to change all-optically the birefringence. This causes switching of the output polarization field back to its input state. This property is useful for all-optical switching. But, when the fiber is initially detuned from its resonance wavelength, and high input powers are used, the switching response depends on which polarization (slow or fast axis) is input into the fiber. We have shown that this asymmetry can be used to make all-optical logic gates.

Shown in Fig. 3 is a self-switching response obtained with 40 ps pulses on resonance when only one polarization is excited. Note the large role that stimulated Raman scattering plays at high input powers, robbing power from the two output channels at the signal frequency.

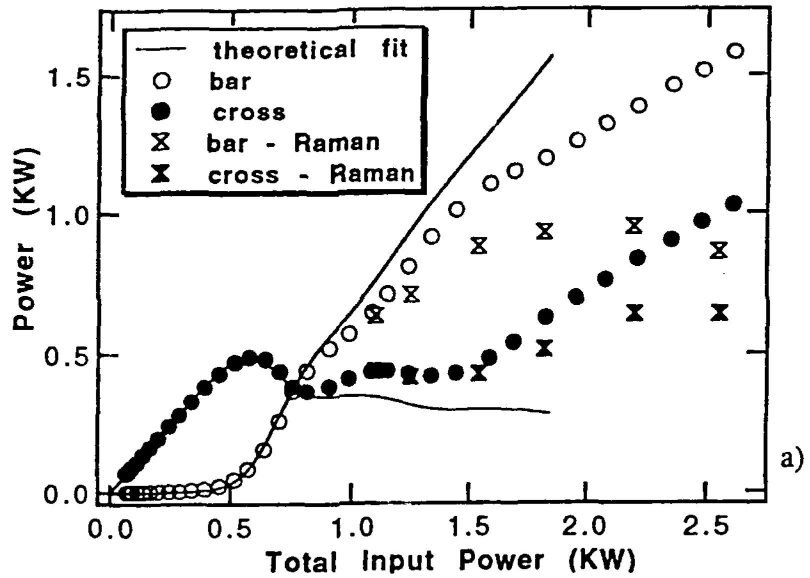

Fig. 3 *Switching characteristics of a rocking filter fiber on resonance.*

In all of the switching experiments reported to date, switching one beam with another uses a strong beam to switch a weak beam. In actual fact, it is desirable to use a weak beam to switch a strong beam, and to be able to control the output channel by varying the properties of the weak beam. This is exactly what has been accomplished here.

Phase-controlled switching in fiber rocking filters has been demonstrated, as shown in Fig. 4.[3] The strong signal is input

into one polarization, and a weak signal (10% of the strong signal) was input into the orthogonal polarization. By controlling the phase of the weak signal relative to the strong beam, the output of the strong signal can be controlled. A comparison between theory and experiment for this effect is shown in Fig 4, and the agreement is excellent.

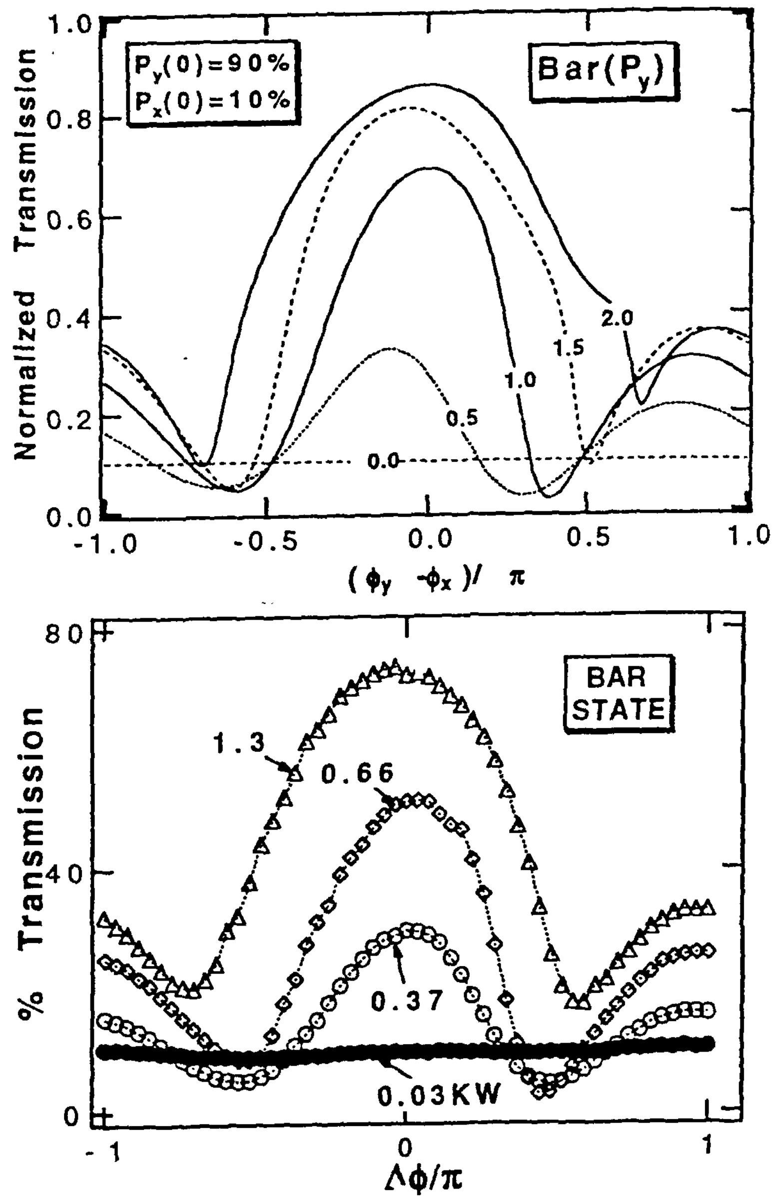

Fig. 4 *Switching characteristics of a rocking filter fiber with a weak probe beam of variable phase (relative to the signal beam) inputted into the orthogonal (to the signal beam) polarization. (a) theory; (b) experiment. P2 is the critical power for switching.*

All-optical logic gates have been demonstrated by initially detuning the input wavelength (λ) from the fiber filter resonance (λ_c), and then using two equi-amplitude inputs, one along each polarization axis.[4] The wavelength and power dependent detuning (δ) is $2\delta = 2\pi[n_x-n_y][\lambda-\lambda_c]/\lambda_c^2 + 0.333\gamma[P_y(z)-P_x(z)]$ where $\gamma = n_2\omega/cA_{eff}$. For $\lambda > \lambda_c$ (and $n_x > n_y$), inputting P_y increases the detuning (decreasing the polarization rotation) and inputting P_x decreases the detuning which increases the polarization rotation. Under the right conditions, either input can lead to a large P_y output, i.e. an OR gate. When two orthogonally polarized inputs are present, detailed numerical analysis shows that XOR and AND gates can also be implemented provided the relative phase between the two inputs is chosen appropriately.

An example of a XOR and AND gate is shown in Fig. 5 for $\delta > 0$.[4] Either an x- or y-polarized input produces a y-polarized output (OR) gate. With both inputs present, the P_y output is zero (small), making this a XOR gate. However, the P_x output only occurs when both pulses are present, i.e. an AND gate.

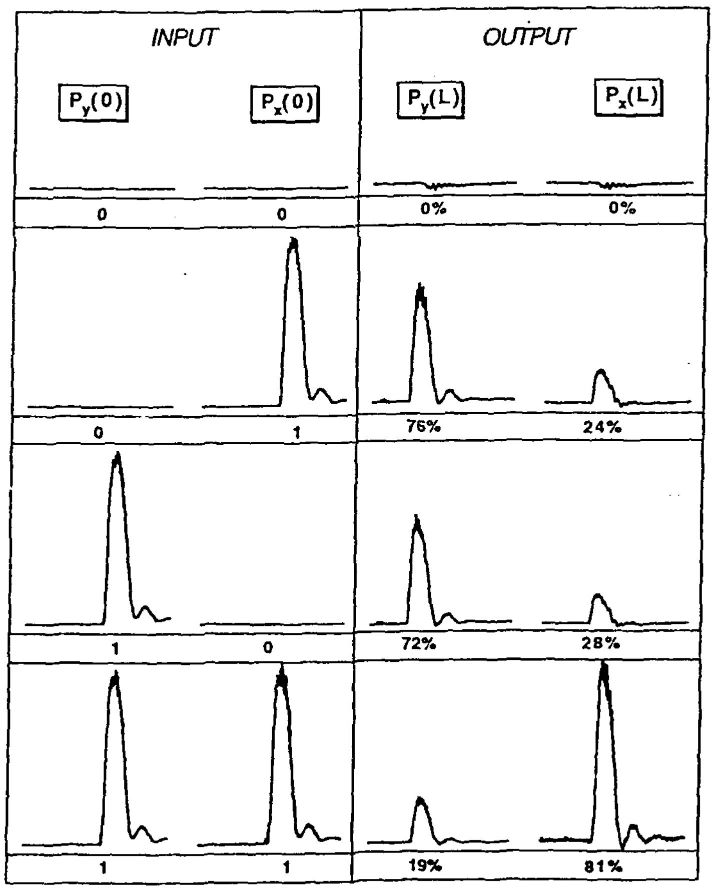

Fig. 5 Input and output signals corresponding to OR, XOR and AND gates.

Demultiplexing of pulses out of a data stream has also been demonstrated experimentally.[6] The idea is that a strong pump pulse at a wavelength far from resonance detunes the filter and hence stops the polarization rotation for a coincident signal pulse at the center filter wavelength. Therefore when a coincidence occurs, the signal is not rotated and can be separated out from the rest of the data stream with a polarizer. The pump power dependence of the fraction of the signal pulse switched is shown in Fig. 6.

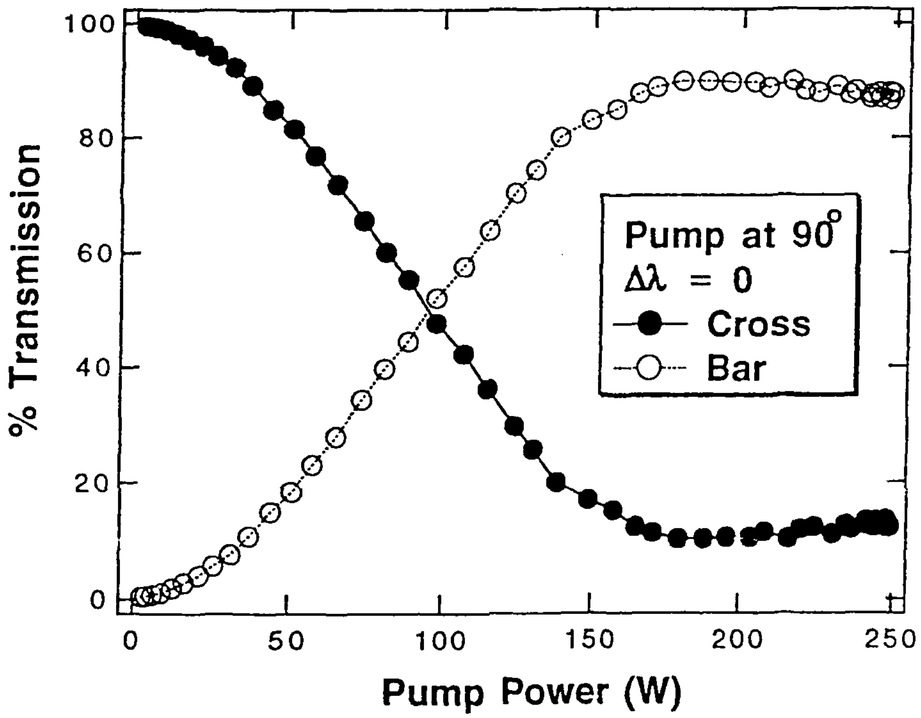

Fig. 6 The fraction of the signal pulse appearing in the two output polarizations versus pump power.

We are currently testing a fiber rocking filter designed specifically for soliton switching at 1555 nm.[7] Our previous calculations have shown that complete switching should be possible with soliton signal inputs. The device was fabricated by Ken Hill of the Communications Research Center in Ottawa Canada. After a few fiber failures due to stress, we now have a device which rotates the plane of polarization through 90^0. Experiments on soliton switching are underway.

3. Femtosecond Difference Frequency Source for 1.5 to 1.8 Microns

A difference frequency mixing source for the infrared has been developed along the lines first reported by Nakazawa and coworkers. It is based on mixing a 200 femtosecond output pulse from a mode-locked Q-switched Sartori dye laser with the 100 ps 1060 nm pulse from the pump mode-locked Nd:YAG Antares laser. In order to increase the output power, the 1060 nm pulses have been compressed to a few picoseconds. The peak pulse power for 250 fsec pulses in the infrared has been about 10 kilowatts.

Although we achieved our original laser objectives, we have discontinued this approach to producing femtosecond pulses in this wavelength range. The prime problem has been the inherent instability of the Coherent Sartori femotsecond dye laser when used with the cavity dumper designed for it. As a result it took all of our time to keep the system operational, leaving no time for experiments.

4. APM Color Center Laser

A Burleigh color center laser has been additively pulse mode-locked (APM) to produce stable pulses with durations variable from 350 to 950 fsec. The current approach to the APM, as developed by Peter Wigley, has led to a reduction of the average laser power by only a factor of two resulting in peak powers of up to 10KW. This is one of the most efficient designs reported to date.

5. Femtosecond Pulse Compression of Solitons Via Higher Order Dispersion

We have demonstrated the compression of solitons down to about 50 fsec by using a combination of higher order dispersion and the soliton self-frequency shift. The basic idea is as follows. Short pulses have a broad frequency spectrum. When this spectrum overlaps that of the Raman spectrum in glass, power flows towards the peak of the Raman spectrum via stimulated scattering. For soliton inputs, this results in a frequency shift of the solitons to lower frequencies (longer wavelengths).

The fibers used had a dispersion in the group velocity dispersion ($\Delta\beta_2$). That is, when the propagation wavevector β is expanded as $\beta = \beta_0 + \beta_1(\omega-\omega_0) + \beta_2(\omega-\omega_0)^2/2 + \beta_3(\omega-\omega^0)^3/6 + ..$, then the value of β_3 determines how the effective β_2 ($\approx \beta_2 + \beta_3(\omega-\omega_0)/3$) changes during the soliton self-frequency shift. Because the pulse width varies as $|\beta_2|$, as the soliton pulse shifts to longer wavelengths it's pulse width is adiabatically reduced provided that $|\beta_2|$ decreases with increasing λ. For the fiber used, we achieved compression down to 50 fsec.[8] A typical result is shown in Fig. 7. The agreement between the experiment and numerical simulations via the nonlinear wave equation was excellent.

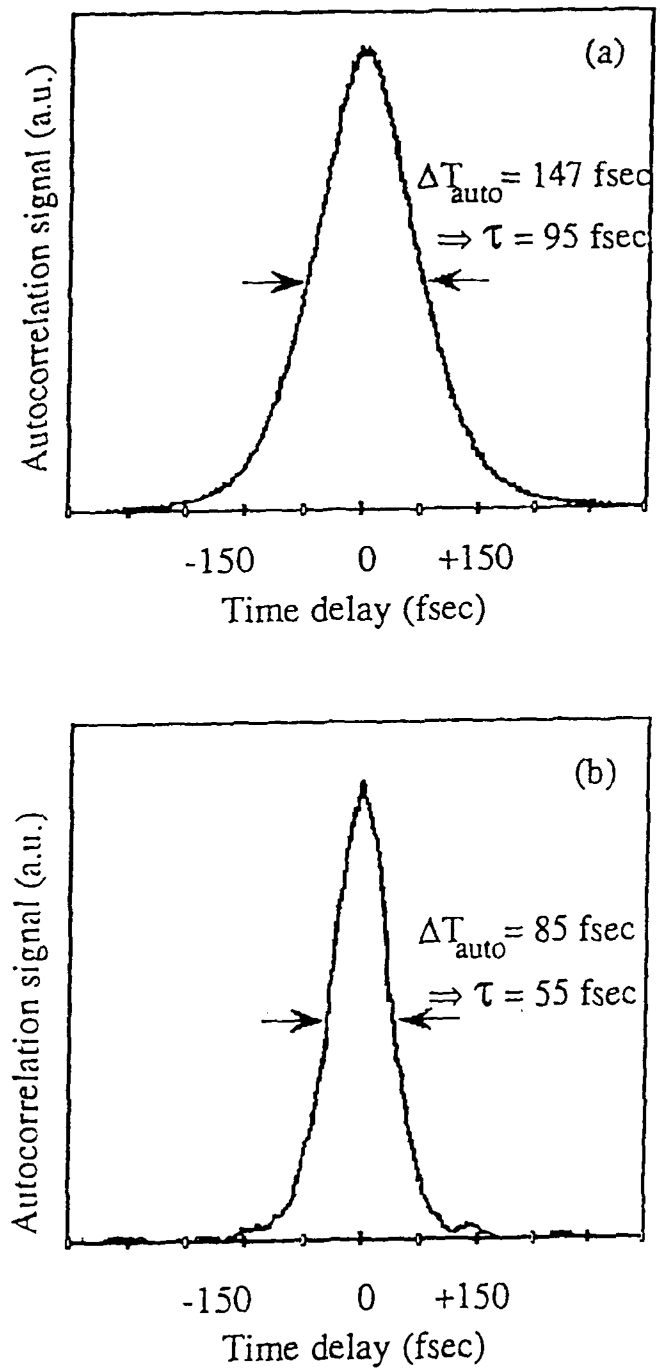

Fig. 7 The autocorrelation of the input pulse (1570 nm) shown in (a) and compressed soliton pulses (1620 nm) in (b).

6. Dual Wavelength Color Center Laser

We have built a two wavelength cw color center laser. By using dispersive elements in the laser cavity, operation at two wavelengths was achieved. The wavelength separation between the two sources was tuned by tilting the etalon plates. A total output power in excess of one watt was realized.

This laser will now allow us to generate periodic trains of bright and dark solitons, at rates of 1 to 100 Gb/sec. This has implications to short haul high density communications.

7. Generation of Periodic Dark Solitons

It has been shown that the mixing of two frequencies in a fiber can lead to the generation of a periodic train of bright solitons in wavelength regions of negative group velocity dispersion. We have been able to demonstrate the converse of this process. That is, the mixing of two frequencies in regions of positive group velocity dispersion leads to periodic dark solitons.

In the experiment we used 10-20 psec pulses from a color center laser whose cavity was misaligned to operate simultaneously at two frequencies near 1540 nm. Dispersion shifted fiber with zero dispersion at 1555 nm was used so that β_2 was positive at the operating wavelength. As the input power was increased, the output evolved into a series of dark solitons superimposed on the pulse profile, and then back to approximately the input pulse profile. The corresponding evolution in the frequency spectrum of the output pulse with input power was also measured. The autocorrelation of the output pulse shape when optimum dark soliton generation occurs is shown in Fig. 8c.

The nonlinear wave equation was used to model this process. Shown in Fig 8a is the calculated dark soliton modulation of the pulse. For comparison with the data in Fig 8c is the calculated autocorrelation given in Fig. 8b. The agreement is excellent showing that indeed dark solitons were generated.

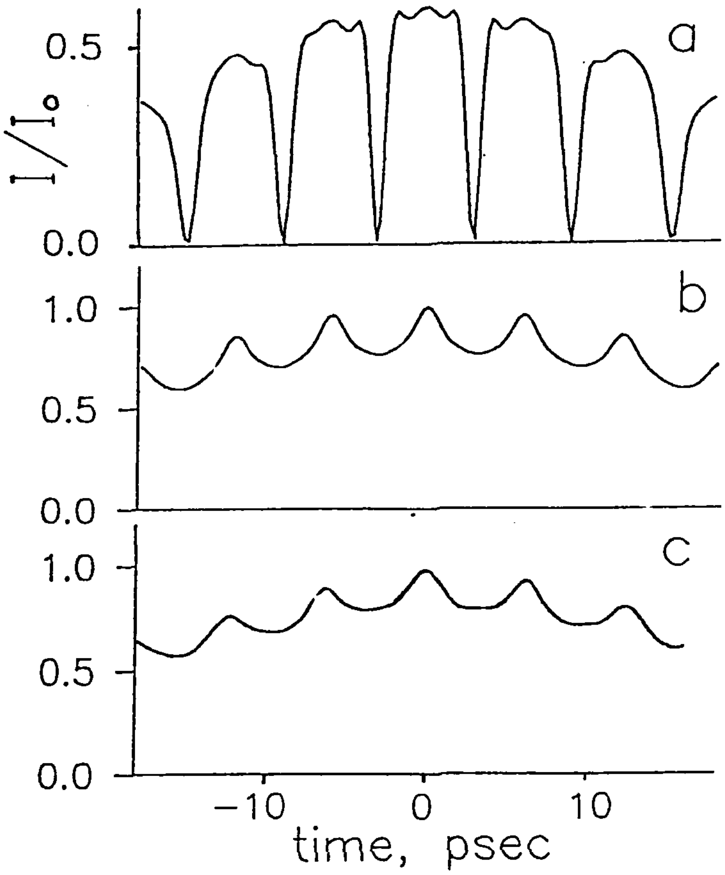

Fig. 8 Train of dark soliton-like pulses obtained with $I_0 = 10^6$ W/cm^2 and $\Delta\upsilon$. (a) - numerical simulation of temporal shape and corresponding intensity autocorrelation function (b). (c) - experimental intensity autocorrelation function.

8. Photosensitivity of Glasses: Sol Gel Films

A project has just been finished to study the photosensitivity in glasses which leads to "Hill" gratings. Here by photosensitivity is meant the multi-photon absorption processes which allow gratings to be written with green light in Ge-doped fibers. The current approach is to study material combinations in formats simpler than fibers, namely sol-gel films. Such samples are easy to produce with a wide variety of precisely controlled ingredients in integrated optics waveguide formats. Joe Simmons and B.G. Potter of the Un. Florida in Gainesville have produced waveguide quality (db/cm losses) thin film waveguides. The growth of gratings has been observed in sol-gel formed films for the first time.

One of the experiments possible in such film waveguides was to study the correlation between hydrogen-atmosphere thermal treatments, absorption at 242nm (oxygen-deficient-germania defect) and photosensitivity. First a linear relationship between loss and length of hydrogen treatment was established, and then related to the index change as measured from grating formation. This is shown in Fig. 9.

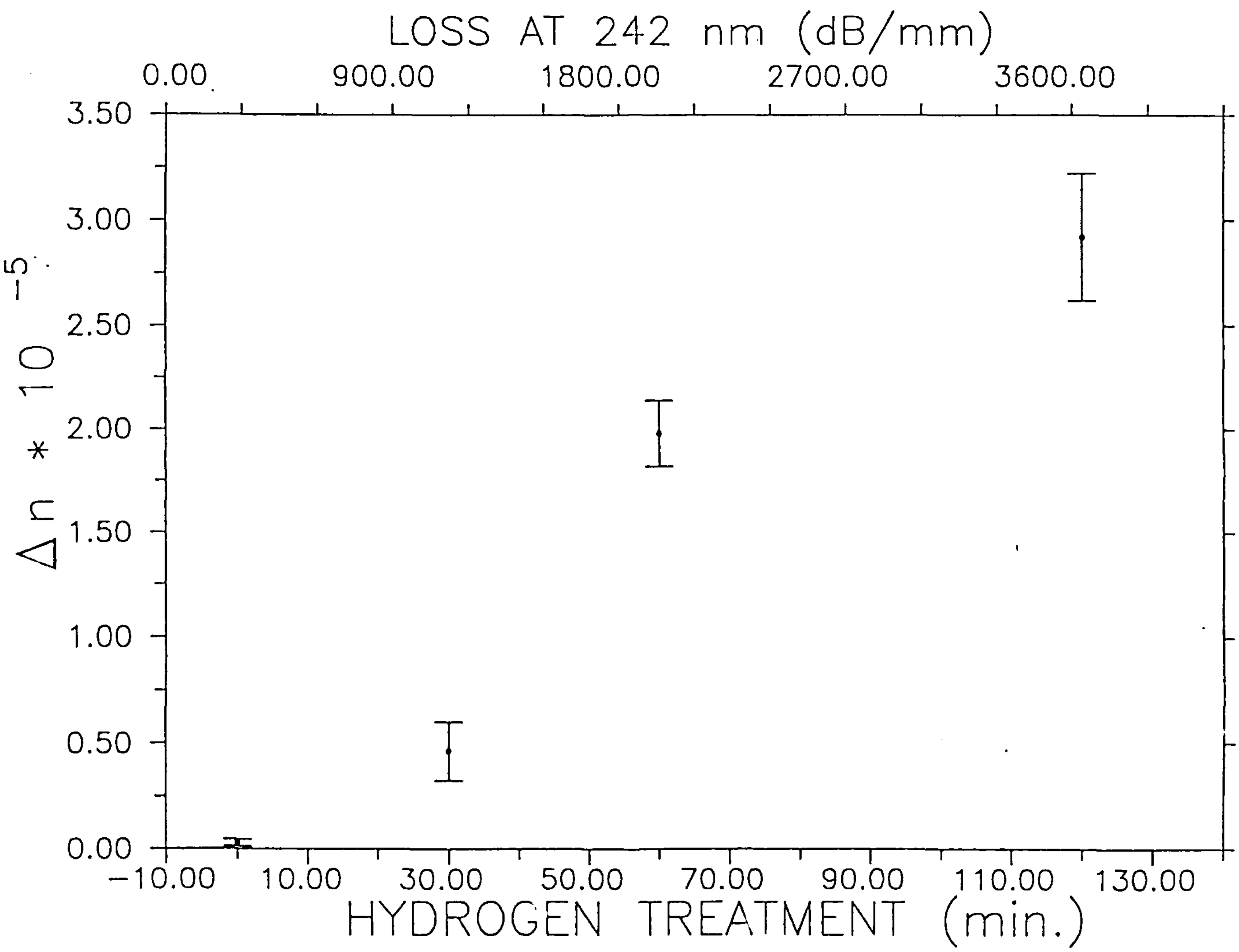

Fig. 9 Induced index change in heat-treated samples vs. exposure time and absorption loss at 242 nm.

A stabilized Mach-Zehnder interferometer was built to measure the relationship between the writing time and the actual integrated refractive index change over the length of the fiber. A single mode He-Ne laser samples the refractive index change produced by a chopped Ar^+ laser. To obtain high sensitivities, the waveguide is placed in one arm of a stabilized Mach-Zehnder interferometer which has a sensitivity of about 1 ppm change in refractive index. By effectively counting interferometer fringes during the early stages of writing the fiber grating, the total refractive index change can be directly evaluated. The measurements have been done and are being currently being analysed.

9. Miscellaneous Nonlinear Fiber Experiments in Tapered Fibers

All-optical switching in a tapered fused coupler was also attempted in collaboration with Suzanne Laval and Jacques Bures of Ecole Polytechnique in Montreal. This device consists of two fibers twisted together and then tapered down to a few microns cross-section by heating and pulling. Unfortunately the initial blew ut the beginning of the experiment. New fibers are now in hand in the form of a Mach-Zehnder interferometer and hopefully the next round of experiments will be successful!

Publications:

<u>(a) Work Completed on Previous Grant and Finally Published</u>

1. V. Mizrahi, S. LaRochelle, G.I. Stegeman and J.E. Sipe, "Physics of photosensitive grating formation in optical fibers", Phys. Rev. A, 43:433-8 (1991).

2. D.R. Heatley, E.M. Wright and G.I. Stegeman, "Spatial ring emission in an optical fiber with nonlinear cladding", Opt. Lett., 16:291-3 (1991)

3. S. Wabnitz, E.M. Wright and G.I. Stegeman, "Polarization instabilities of dark and bright simultons in birefringent optical fibers", Phys. Rev. A, 41:6415-24 (1990)

4. S. Wabnitz, S. Trillo, E.M. Wright and G.I. Stegeman, "Wavelength dependent soliton self-routing in birefringent fiber filters", JOSA B, 8:602-13 (1991)

5. K.D. Simmons, S. LaRochelle, V. Mizrahi, G.I. Stegeman and D.L. Griscom, "Correlation of defect centers with wavelength dependent photosensitive response in germania-doped silica optical fibers", Optics Lett., 3:141-3 (1991)

(b) Work Submitted or Published Under New Grant

6. J. Wilson, G.I. Stegeman and E.M. Wright, "Soliton switching in an erbium-doped nonlinear fiber coupler", Opt. Lett., 16:1653-5 (1991)

7. C.G. Krautschik, G.I. Stegeman and R.H. Stolen, "Phase controlled all-optical switching in rocking filter fibers", Appl. Phys. Let., 61:1751-3 (1992)

8. C.G. Krautschik, G.I. Stegeman and R.H. Stolen, "Asymmetric Response of a Nonlinear Fiber Rocking Filter: All-optical Logic Gates", Opt. Lett., submitted

9. C.G. Krautschik, P. Wigley, G.I. Stegeman and R.H. Stolen, "Demonstration of demultiplexing with a rocking filter fiber", Appl. Phys. Lett., submitted

10. D.C. Johnson, F. Bilodeau, B. Malo, K.O. Hill, P.J.G. Wigley and G.I. Stegeman, "Long length, long period rocking filters fabricated from conventional monomode telecommunications optical fibre", Opt. Lett., 17:1635-7 (1992)

11. K.D. Simmons, G.I. Stegeman, B.G. Potter Jr., J.H. Simmons, "Photosensitivity of sol-gel derived germano-silicate planar waveguides", Optics Lett., in press

12. J. Wilson, G.I. Stegeman and E.M. Wright, "All-optical switching of solitons in an active nonlinear directional coupler", J. Opt. and Quant. Electronics, 24:S1325-36 (1992)

13. S.P.V. Mamyshev, P.G.J. Wigley, J. Wilson, G.I. Stegeman, V.A. Semeonov and E.M. Dianov, "Observation of adiabatic compression of fundamental solitons in optical fibers with higher-order dispersion", Phys. Rev. Lett., submitted

(c) Conference Presentations (* denotes invited)

1. J. Wilson, G.I. Stegeman and E.M. Wright, "Soliton switching in an erbium-doped nonlinear fiber coupler", Annual OSA Meeting, November 1991

2.* G.I. Stegeman, "Introduction to Nonlinear Guided Wave Phenomena", NATO Advanced Institute on Nonlinear Guided Wave Phenomena, Cargese, August 1991

3.* G.I. Stegeman, "All-Optical Switching Devices: Fiber Versus Integrated Optics", 16'th Australian Conference on Optical Fibre Technology, Adelaide, December 1991

4.* G.I. Stegeman, "Material Requirements for Nonlinear Third Order Phenomena in Waveguides", Toyota Conference on Nonlinear Optics, Nagoya, October 6-9, 1991

5.* G.I. Stegeman, ""Ultrafast All-Optical Switching", AAPT Winter Meeting, January 1992

6.* G.I. Stegeman, "All-Optical Switching in Fibers", INOE 50'th Anniversary Lectures on Nonlinear Photonics, April 1992

7.* G.I. Stegeman, "Current Topics in Nonlinear Guided Waves", Summer School on Nonlinear Photonics, June 1992

8. C. Krautschik, G.I. Stegeman and R.H. Stolen, "Coherent Ultrafast All-Optical Switching in Fibers", Topical Meeting on Ultrafast Phenomena, June 1992

9. C. Krautschik, G.I. Stegeman and R.H. Stolen, "Coherent Ultrafast All-Optical Switching in Fibers", Topical Meeting on Nonlinear Optics, August 1992

10. C. Krautschik, G.I. Stegeman and R.H. Stolen, "Phase-Controlled All-Optical Switching", OSA Annual, September 1992

11. P.V. Mamyshev, P.G. Wigley, J. Wilson and G.I. Stegeman, "Observation of Adiabatic Compression of Fundamental Solitons In Optical Fibers with Higher-Order Dispersion", OSA annual 1992, postdeadline paper, September 1992

12.* G.I. Stegeman, C. Krautschik and R.H. Stolen, "Nonlinear Fiber Filter: Demonstration of Phase-Controlled Switching, Optical Logic and Demultiplexing", Workshop on Materials and Devices for Ultrafast All-Optical Switching, October 1992

13. C. Krautschik, G.I. Stegeman and R.H. Stolen, "Asymmetric Wavelength Response of Nonlinear Fiber Rocking Filter: Applications to All-Optical Logic Gates", CLEO'93, submitted, May 1993

14. P.V. Mamyshev, P.G. Wigley, J. Wilson and G.I. Stegeman, "Nonlinear Excitation of Dual-Frequency Laser Pulses in an Optical Fiber with Positive Group Velocity

Dispersion", CLEO'93, submitted, May 1993

15. K. Simmons-Potter, B.G. Potter, J. Simmons and G.I. Stegeman, "Photosensitivity and Optical Properties of Germano-Silicate Sol-Gel Planar Waveguides", Gordon Conference on Optical Phenomena in Glass, June 1992

PhD Theses:

1. Christof G. Krautschik, "Nonlinear Polarization Switching and Logic Operation with Rocking Filter Fibers", PhD, University of Arizona, 1992

2. Kelly Simmons-Potter, "Photosensitive Processes in Germano-Silicate Waveguides", University of Arizona, Spring 1993